

# **National Aeronautics and Space Administration**

**Computing, Information and Communication Technologies Program  
Information Technology Strategic Research Project  
Intelligent Controls and Diagnostics Sub-Project**

## **Integrated Computational Dynamics and Diagnostics Task UPN 302-05 FY04 Plan**

Agreements:

\_\_\_\_\_  
Joseph J. Totah  
Approve: Level III ICD Sub-Project Manager

\_\_\_\_\_  
Date

\_\_\_\_\_  
Dr. Edward M. Huff  
Submit: Level IV ICDD Task Lead

\_\_\_\_\_  
Date

## Program Overview

The newly named Integrated Computational Diagnostics and Dynamics (ICDD) program element represents the core computational sciences research that has been supported by CICT for several years under the rubric Intelligent Health and Safety Monitoring (IHASM). The earlier program also included a rollup of several aeronautical application projects that had been slowly inherited from the NASA Rotorcraft (R/C) and Aviation Safety (AvSP) programs. These higher Technology Readiness Level (TRL) thrusts, primarily oriented to component health monitoring, will be transitioned back to these programs in a manner consistent with the Agency's "One-NASA" policy.

A unique aspect of ICDD research been the evolution of a very close working relationship between investigators at Ames and Glenn, who share flight and test-rig resources to address the challenges of developing effective damage detection and prognostics technology. At both Centers, Army contributions have also been essential for access to mechanical component test-rigs and research aircraft. Working together, several major breakthroughs have been made in standardized data measurement, including the development of information processing hardware and software for use with test rigs (e.g., ALBERT) and research aircraft (e.g., "Healthwatch"). More importantly, these capabilities have established a basis for scientific data collection and analysis, which provide important insights into the underlying limitations of present health monitoring methods. On the whole what has been learned is that, in the future, successful damage detection methods must take into account the dynamical influences of real-time vehicle operations, which result in highly non-stationary signals and nonlinear signal response surfaces. *Developing effective computational methods to integrate real-time diagnostics and dynamics information, therefore, is a critical area for enabling successful vehicle health monitoring.* This, in turn, will depend upon maintaining an interdisciplinary research team with expertise in such disciplines as classical statistics, signal analysis, data fusion, control theory, and computer engineering.

During the latter part of FY-03, several notable events occurred. First was the successful submission of a US Patent by Dr. Upender Kaul containing the discovery of a general method for automated two- and three-dimensional elliptic grid generation. Now, for the first time, a computational method exists to model structural changes and damage progression over time. The technique also has the potential for many exciting commercial applications in diverse areas. Second, with recent support from the CICT program, Mr. Donald Soloway and Dr. Atul Kelkar successfully completed a formal stability proof of Generalized Predictive Control (GPC). This prepares the way for a broad range of potential GPC applications, including dynamic signal analysis, as mentioned above, as well as the control of complex, flexible, structures such as those envisioned for future JIMO missions. Third, in mid-August 2003, Healthwatch-2 (HW-2) software conceptualized by Dr. Edward Huff was flown successfully on the Ames OH-

58C. This research capability now makes it possible to explore a wide range of discontinuous signal averaging (DSA) techniques based on the vehicle's momentary position in logically defined state spaces. This capability is also being implemented on the C-17 at DFRC, and future versions of ALBERT at GRC.

Finally, recognizing these and related accomplishments, the US Army Vibration Monitoring Enhancement Program (VMEP) has proposed to instrument a Black Hawk helicopter at Ames with the open-architecture VMEP kit. This offer from the Army's VMEP program manager reflected explicit recognition of ICDD's applied value, and provides an exceptional migration path for maturing NASA computational technology. The potential collaboration recognizes not only Ames' flight research but also Glenn's, which includes earlier development of classic damage metrics, oil-debris analysis, and, sensor fusion.

## **Program Restructuring**

In most instances a clear distinction can be made between the *discovery* of computational principles and their subsequent use. Indeed, in this regard it is evident that the major successes of the program, discussed above, are general advances in information technology and computational science. Unfortunately, perfectly clear distinctions cannot always be made between the research infrastructure needed for scientific data collection or analysis (see below), and much the same resources used for applied development or demonstration. This issue will require a satisfactory resolution.<sup>1</sup>

Starting in FY-05, therefore, a realignment of the overall effort will begin in conformity with Code R restructuring guidelines. This is seen as a valuable exercise, since a number of ongoing application activities are highly pertinent to evolving Rotorcraft (R/C), and the Aviation Safety and Security (AvSSP) program objectives. As discussed above, it will be attempted to associate higher TRL elements, such as VMEP applications, with the Rotorcraft program, and future C-17 engine monitoring applications with AvSSP.<sup>2</sup>

### **Addressing Aerospace Requirements.**

The research activities in the ICDD program were motivated initially by needs for intelligent real-time component health monitoring in operational aircraft. These needs

---

<sup>1</sup> ICDD will continue to provide moderate funding to the FPO to assure the flow of scientific flight data from the OH-58 and UH-60 helicopters.

<sup>2</sup> This is being made difficult by full-cost accounting policies, which are still being formulated.

are clearly evident in helicopters, which depend entirely upon rotating mechanical components to sustain flight, but are also manifest in transport engines and, potentially, space vehicles. In the case of space vehicles the boundary requirements are quite different, in that damage detection would serve mainly to inform operators a considerable distance away as to the status of the vehicle (e.g., rover, remote-agent, etc.). Although such diagnostic or prognostic information might prove useful in mission planning and tactical decision-making, the strongest needs will probably occur in the future with the advent of permanent space habitats with a supporting maintenance infrastructure as is currently being discussed.

With the realization that the dynamical control behavior of the vehicle is inextricably related to the physical signals that are observed, e.g., vibration, debris, control responses, etc., it has also become clear that automated health assessment must ultimately involve a blend of vehicle control and structural response information. This, in turn, broadens the conceptual framework and provides a synergy between certain aeronautical and space applications. For example, particular types of space vehicles, such as those currently envisioned for the JIMO mission, involve a number of articulated elements as well as a highly flexible structure. A sophisticated control system, therefore, must guide and orient the whole vehicle properly, while monitoring, identifying, and suppressing vibration responses inherent in the structure. Changes in the patterns of vibration may, in turn, provide essential information to infer physical problems, either with the craft's structure or its mechanical articulation mechanisms. Although several theoretical constructs may prove suitable for integrating diagnostics and control dynamics, it is felt that the theory of Generalized Predictive Control (GPC) has several properties that make it a good starting point.

### **New Program Elements**

Given these circumstances, the transitional FY-04/05 program includes provision for:

- VMEP implementation on an Ames Black Hawk.
- Expanded focus on multivariate damage detection techniques (e.g., factor analysis, data fusion, etc.).
- Exploration of GPC theory as a computational framework for integrated diagnostics and dynamics.
- Evaluation of concurrent spacecraft control and component monitoring in flexible, articulated, spacecraft structures.

### **Future Program Support**

Although it is sketchy exactly how budget or manpower adjustments will be worked out by FY-06, this year's plan is presented in two general sections pertaining to:

- (A) core information technology or computational research

(A) potential future aerospace monitoring or control applications. Consistent with the new name of the program, it is anticipated that the core research contained in Section A, “*Integrated Computational Diagnostics and Dynamics*,” will be retained as a basic, low-TRL crosscutting activity. Programs like Rotorcraft, Aviation Safety and Security (AvSSP), and JIMO are expected to provide support for vehicle specific monitoring or control applications as discussed in Section B.<sup>3</sup>

## **General Objective**

***The primary goal of the program is to synthesize machinery diagnosis, prognosis, and vehicle control principles into a unified computational framework based on physical, structural, and dynamical models. Future vehicle system applications using software containing these principles are expected to demonstrate greater robustness, adaptability, and intelligence.***

### **Specific Sub-Objectives:**

- Establish a comprehensive understanding of design, manufacturing, installation, flight control, and fatigue effects on observable signals such as vibration, breakdown products, and system control responses.
- Experimentally determine the statistical signatures of vibration, torque, and other signals under dynamic operating conditions.
- Develop first-principles modeling techniques to produce canonical reference signatures that aid in optimal damage identification.
- Explore theoretical constructs that lend themselves to the synthesis of damage detection and vehicle control.
- Develop effective (i.e., high “hit” and low “false-alarm”) algorithms for real-time damage detection under dynamic operating conditions.
- Employ statistical techniques (e.g., Monte Carlo, Bootstrap, etc.) to construct synthetic anomaly distributions for robust damage detection and control validation.
- Develop database methods to facilitate broad scientific and industrial access to the growing body of US Govt. data generated during the program.

### **Skills Required.**

The research skills needed to address these objectives include expertise in several disciplines including but not limited to: experimental statistics, signal analysis, control

---

<sup>3</sup> As of this writing, AvSSP generally classifies this work “over guidelines” for FY-06 and beyond. The Rotorcraft Program recognizes the need for diagnostics technology inputs, but there are unresolved manpower and funding issues related to full-cost accounting. Also, FY-06 new initiatives are being developed by the Agency. It is believed that future JIMO consulting activities will result from a competitive selection process.

theory, decision theory, first-principles modeling, structures, engineering mechanics, and computer/software engineering.

## **Research Infrastructure**

### **Test Rigs.**

As part of ongoing cooperative research program between Ames and Glenn Research Centers, experiments continue to be performed in the 500 HP OH-58C Transmission Test Rig and other unique gear and bearing test facilities at NASA Glenn. These facilities allow systematic study of both materials and structures problems, such as crack propagation, bearing defects, lubricant degradation, and planetary system functioning within the framework of real mechanical components and supporting structures. Within certain limits, the results can be reasonably generalized to other complex equipment systems, such as advanced gear drive engines, which are only now on the drawing board.

### **Flying Laboratories.**

Research aircraft located at Ames and Dryden may be thought of as “flying laboratories” and continue to be used to provide empirical data, and evaluate computer algorithms in-flight, that are essential for model construction and validation. The influences of dynamic flight can be measured only in such facilities. Considerable NASA investments were made instrumenting the OH-58C and AH-1S helicopters at Ames, as well as the C-17 at Dryden.<sup>4</sup> It should be noted that these aircraft are not only specimens from their respective vehicle populations, but also important *surrogates* of other mechanical systems of related design. For example, current constant-speed-engine helicopters employ planetary systems for output load distribution. These can be used to anticipate the needs of advance geared-fan transport engines that will use planetary or similar gear system designs.<sup>5</sup> Conversely, transport engines, such as those on the C-17, are variable speed devices that may be used as *surrogates* for future variable-speed-engine helicopters.

### **Databases.**

The raw and derived data files generated by the ICDD program constitute an expanding database of growing national importance. The fact that one helicopter at Ames was decommissioned during FY-02 actually lends weight to the uniqueness of the legacy data it provided, since comparable scientific quality cannot be readily obtained elsewhere. As researchers manipulate data for various purposes, many sub-files are created which must be distributed to assure comparability. These derived files must also be shared with outside researchers subject to security and export control. As large amounts of data are

---

<sup>4</sup> Unfortunately, the AH-1S Cobra was decommissioned in 2002, eliminating that avenue of data.

<sup>5</sup> This view is strongly supported by Pratt & Whitney.

added in the future from the C-17 and EH-60L, the database system developed at Ames will become even more significant.

## **Section A: Core Research:**

### **Integrated Computational Diagnostics and Dynamics**

#### **Statistical Modeling.** (Edward Huff, ARC)

Using multivariate methods, the statistical properties of flight data are being analyzed specifically to understand the nature of speed, torque, fuel depletion, and other effects on the time/frequency characteristics of measured signals. Since the variance of recorded time series reflects the influences of both known and unknown deterministic processes, as well as random noise, attention is focused on computational methods for “correcting” the signals for these effects. The most commonly used method is continuous signal averaging, in either the time- or frequency-domain, but this has shown to be inadequate if not dangerously misleading for flight applications due to underlying non-stationarity dynamics.

Work reported at the AHS-2001 and 2002 Annual Forums that examined and compared the three-dimensional responses of the AH-1 and OH-58C helicopters using PCA, was expanded in FY-03 to include mesh frequency power distributions. This approach parsed the total power (i.e., RMS) in each principal axis, and was combined with an exploratory state-space analysis defined by instantaneous engine torque, torque derivative, and output shaft speed. The paper presented at the AHS-2003 Forum demonstrated the highly complex, non-linear nature of the vibration response surface. It also revealed that a single 2-hr. mission is, at least for the OH-58C, inadequate to capture a sufficient number of points within the state-space to model the surface. If this observation holds for heavier vehicles, the broad implication is that in-flight systems will need sufficient intelligence to learn (i.e., adapt to) the specifics of each vehicle over time.

During FY-04, the OH-58C flights discussed above are being re-flown with more stringent recording of pilot observations and the addition of GPS information. These will be compared with the earlier data, and multivariate techniques, such as factor-analysis, used to identify “hidden” or latent variables that may be inferred from the response covariance matrix. These same techniques will also be applied to legacy AH-1 data collected in FY-01, where aircraft attitudes were recorded that allow for a more comprehensive state-space analysis. These results will be reported at AHS-2004 in 3Q04

#### **Multivariate Sensor Fusion.** (Paula Dempsey, GRC)

The reliability and accuracy of detecting damage in rotating machinery is a direct function of the accuracy of the physical sensor and corresponding diagnostic techniques being used. Studies have shown that by integrating the signals and features from a variety

of sensors, the integrated system showed improved detection and decision-making capabilities as compared to using individual measurement methods. This is especially true for those failure modes for bearings and gears that generate both wear debris in the oil and vibration signatures when failure occurs. In this effort, multivariate decision fusion will be used to develop diagnostic tools to accurately and reliably detect bearing and gear damage on-line.

Work will be completed by 4Q04 on a general purpose diagnostic software tool being developed and evaluated experimentally with gear & bearing vibration and oil debris data from NASA Glenn Test rigs, e.g., the 500-HP Helicopter Transmission Test Facility, Spur Gear Fatigue Rig, Spiral Bevel Gear Fatigue Rig, etc. Multivariate decision fusion schemes being incorporated for planetary fault detection using vibration, oil debris, and acoustic emission data from test rigs and transport aircraft as they become available.

By 4Q04, planetary tests on the OH-58C will be completed. The Bearing Diagnostic Test Rig should be completed by 3Q04, and several oil debris analyzers will be evaluated for incorporation in the lab facilities. These are planned to be consistent with flight equipment also being evaluated for installation on the ARC EH-60L aircraft during FY-04, thereby providing a coherent basis for ground and airborne research on oil-debris data fusion.

**First-Principles Modeling.** (Upender Kaul, ARC)

To identify the unique vibration characteristics of a specimen gear system, the most complete approach is to compare its output with that of a physics-based computational model, which represents what the *design gear system* would produce under the perfect operating conditions. This is being pursued by a first-principles, finite-difference modeling effort that was expanded in late FY-02 with the purchase of a dedicated SGI computer system. To date several breakthroughs have been made, including a seminal publication in the Journal of Computational Physics, as well as an official US Patent submission concerning methods to automatically generate optimal 2D and 3D elliptic grids on demand. Using this technique, it is anticipated that nominal “reference” vibration signatures will start to become available by 3Q04. Starting in 4Q04 “ideal” damage signatures will begin to be produced for various problems of interest. Since highly intensive computing is required, NAS facilities will most probably be used.

Structural Dynamics Simulator (Simulator): In FY03, work was carried out to improve the accuracy of the Simulator’s predictions. Work on the boundary condition formulation based on the theory of hyperbolic systems is being carried out in 1Q04. Numerical simulations with the Simulator reported in FY03 validated the three-dimensional structural dynamics simulator, by comparing the predictions with the closed form solutions for a rotating thin disk (2-D) and a rotating shaft (3-D). The implementation of boundary conditions for these two test cases was made possible by deriving them from the corresponding analytical solutions. But, for gears in mesh, general hyperbolic



boundary conditions have to be derived to make the corresponding predictions. Papers involving this work will be sent to the appropriate forum for presentation and to an appropriate journal by 3Q04.

**Animator:** Work was done in FY03 to improve the animator, which now not only displays the predictions graphically in simulation time, but can also be interrupted and checked for anomalies either in the grids or the physical quantities that are displayed and then resumed. The evolving grids can now be inspected in three-dimensional space by rotating, zooming or translating them on the screen, at any point during the simulation. This capability will be further developed in FY-04.

**Generalized Predictive Control (GPC).** (Donald Soloway, Ames, and Atul Kelkar, Iowa State U.)

Over last decade GPC has emerged as one of the leading control design strategies for robust control of dynamical systems. In early years (prior to late eighties) GPC's applicability was essentially limited only to process control applications due to its demand on computational speeds. However, with the advances made in the computer technology over last decade computational speed is not a major concern for many real-life applications and control engineers have started using GPC for many mainstream applications. In recent years, GPC has become a viable alternative or in some cases even a preferred choice over well-known H-infinity,  $H_2$ , and  $\mu$ -synthesis approaches. It has proved to be very effective when requirements of robustness and performance are hard to achieve with traditional control designs. The architecture also lends itself to incorporate model adaptation, such as parameter identification, or updating schemes including neural network-based algorithms. Finally, low-level mission-critical information is naturally available to be interfaced with health monitoring systems.

As part of a collaborative grant to Dr. Kelkar at Iowa State University, targets to be addressed in FY-04 include:

- A systematic synthesis procedure for the end-point weighting matrix (a design parameter to be chosen for stability guarantees)
- Architecture for formation flying
- Realistic cost function for autopilot commands
- Extended collision avoidance in 6-DOF
- Implement the two-tier nested GPC architecture
- Expansion of the overall GPC architecture to synergize with health monitoring objective functions.

**Planetary Decomposition Algorithms.** (Marianne Mosher)

Advanced gear drive engines will employ star, planetary, or differential gear systems that are very difficult to analyze because several identical planet gears influence the composite signal simultaneously. Several program efforts are underway at Ames and

Glenn to address this formidable problem. At Ames the focus is the development of a planetary separation algorithm. At Glenn strain gages will be placed on the planetary ring gear teeth and used to validate current planetary dynamics and tooth stress models. The basic objective is to separate the measured signal into additive parts that represent the individual planet gears in the system.

It is anticipated that an Ames planet separation algorithm will be ready for in-flight testing by 3Q FY-04, and that corroboration will be accomplished using the available database as well as Glenn test-rigs. Flight evaluations of the Ames or U. Maryland algorithm are being considered for FY-04 on the OH-58C.

Other specific work planned for FY-04 in this area includes analysis of UH-60 planetary carrier crack data from Redstone, and Single Value Decomposition (SVD) modeling of spectra from flight tests. Several papers have been accepted for conference presentations during the year including two at the AHS Annual Forum, and one at the annual JANNAF meeting.

**Database Development.** (Jeff Lee)

Dr. Jeff Lee completed design and demonstrated of the Ames database system (SigView) on schedule in 2Q FY-03, and efforts to connect it to the Army's VMEP database will be explored during FY-04 in conjunction with VMEP implementation. At the moment the database is being populated with legacy data as well as voluminous raw data files from current OH-58C flights. Necessary expansions may require the purchase of more robust data storage devices, or COTS software that can be tuned to the overall database design requirement.

## **Section B: Technology Applications**

**Rotorcraft Program.** (Army/Ames/Glenn)

During the first quarter of FY-04 the Army will install a VMEP kit in the Ames EH-60L Black Hawk helicopter as a means to capture NASA information technology for HUMS applications.<sup>6</sup> This would provide an initial experience for migrating NASA's information technology to fielded systems, and will also be explored for its research potential. The Black Hawk is a heavy system, with two engines and a complex, combined transmission that offers new research challenges for real-time health evaluation. Hence, the desirability of developing a NASA Healthwatch capability for the Black Hawk will be examined and included in a Rotorcraft Program proposal.

---

<sup>6</sup> The kit and non-recurring installation costs will be provided at Army expense. Negotiations are in progress concerning continuing research support by both agencies.

Although it is somewhat early to provide detail, the prospect of a heavy, well instrumented, helicopter at Ames has tremendous implications for impacting future “heavy-lift” passenger-carrying transport vehicles. It is generally believed that the market viability of such transports will depend in no small part on the vehicle’s robust health management system. Proposed Rotorcraft Program activities will also include the integration of an oil debris monitor and data fusion technology.

#### **Aviation Safety and Security Program (AvSSP) (Ames/Glenn)**

Although engine-related failures only account for between 6% to 9% (1) of the primary causes for accidents involving Part 21 aircraft (all commercial airplanes with 30 or more passengers), engine related incidents are a potential safety issue that will continue to increase as airlines are forced to reduce operational costs, and delay purchasing newer equipment. Although the majority of in-flight engine-related incidents result in few accidents and fatalities, these incidents usually require emergency procedures to be implemented by the flight crew, resulting in a higher probability of pilot error and/or additional aircraft damage. A recent study of Part 21 aircraft has shown that in only one year there were a total of 76 engine in-flight incidences involving engine malfunction. Of these, 20 were engine failures, and 34 resulted in crew-initiated in-flight engine shutdowns. Of these, a majority is due to mechanical systems problems, such as oil systems failure, bearing failures, etc.

This task will develop the technologies to significantly reduce engine-related failures and incidences for all aero-propulsion systems. The work proposed would focus on developing accurate and highly reliable health management technologies to detect damage of major mechanical systems, and predict, in a timely manner incipient failure that would otherwise not be detected until total systems failure.

#### **Major elements proposed:**

- Apply techniques to produce stationary data from a variety of vibration and oil monitoring sensors that are strongly influenced by flight conditions and maneuvers. Evaluate effectiveness using data from OH-58 and C-17 flight test beds
- Develop reliable and accurate component damage and system anomaly detection by integrating a variety of vibration and oil sensors using advanced data fusion/fuzzy logic methodologies.
- Validate component damage and system anomaly detection technologies using in-house fatigue and system test rigs.
- Evaluate predictive health management technology in-flight. Verify elimination of in-flight false alarms

**Deliverables:**

FY07: Demonstrate methods to stabilize signals and eliminate influence of operational and flight conditions.

FY08: Validate component damage detection & systems anomaly detection using failure progression data from component and systems test facilities.

FY09: Validate dynamic component and systems models for predict normal and anomalous conditions

FY09: Complete integrated predictive health management tool. Verify using test rig data.

FY10: validate, in-flight, predictive health management model for critical mechanical systems.

**JIMO Program Submission**

(Ames/Iowa State U.)

In preparation for a NASA research announcement in FY-05 concerning the multifaceted JIMO control system, additional work is being performed within the collaborative grant to Prof. Atul Kelkar mentioned above under Generalized Predictive Control (GPC). The effort is organized around the following preliminary conception of JIMO requirements, which will be refined during FY-04:

**Performance Needs:**

- Maintain stability during various maneuvers - cruising, orbit. boosting/degrading, turning and re-orientation, etc.
- Accommodate wide range of pointing requirements.
- Minimize structural vibrations for better accuracy and prolonged structural life.
- Robustness to plant uncertainties and disturbances.

**Other Capabilities:**

- Ability to respond to degradation of components or systems over time.
- Reconfiguration ability to accommodate partial system malfunctions or damages.

## Program Milestones

<b>PCA 8 Project/Sub-Project Milestones</b>	<b>Due Date</b>	<b>Metrics</b>
<i>8.6 Demonstration of propulsion health management technologies for engine performance enhancement and component health and safety monitoring.</i>	<i>Sep-06</i>	<p><i>(1) An adaptive control system for turbine casing cooling flow to accommodate the effect of engine degradation on turbine clearance. Maintain design efficiency of the turbine as the engine degrades by maintaining the clearances to the design level, resulting in increased engine life due to reduction in rate of exhaust gas temperature degradation and consistent performance over the engine life.</i></p> <p><i>(2) Development of HealthWatch III (HW-3) including a programmable data acquisition system and the ability to sample and store high-speed data in operation. A health monitoring system for integrated real-time sampling of both vibration and oil-debris signals for advanced damage detection of incipient component degradation.</i></p>
8.6.1 Engine simulation demonstration of smart life extending control using stochastic based life models. (ICDPS)	Sep-03	The engine control will adapt to current engine condition with the objective to minimize future damage accumulation. Improved engine control will result in increased engine on-wing life and reduction in maintenance cost.
8.6.2 Demonstrate in-flight vibration monitoring module for mechanically geared engines and transmissions. (ICDD)	Sep-04	Demonstration of HealthWatch II (HW-2) health monitoring system. In-flight data acquisition capability that includes revolution counting and discontinuous time synchronous averaging features essential for the development and use of similar capabilities on transport aircraft for advanced engine monitoring.

<b>PCA 8 Project/Sub-Project Milestones</b>	<b>Due Date</b>	<b>Metrics</b>
8.6.3 First flight demonstration of health management technologies for subsystem performance enhancement and component health and safety monitoring. (ICDD)	Sep-05	First flight demonstration of HealthWatch III (HW-3), including a programmable data acquisition system and the ability to sample and store high-speed data in operation. First flight data collected from both vibration and oil-debris.
8.6.4 Post flight test analysis, reporting, and outreach. (ICDD)	Sep-06	Final report on flight test demonstrations, and print/multi-media development for educational outreach and external affair. NASA Technical Memorandum or NASA Technical Paper documenting the approach, methodology, and experimental/experimental results that can be used as a substantive reference upon which future work can build upon. A conference paper and/or journal article in a relevant professional forum will also be presented so that the results can be shared with the technical community at large.

**Task Milestones and Schedule (FY04 approved, FY05 and beyond planned))**

**LIII: Synthesize machinery diagnosis, prognosis, and vehicle control principles into a unified computational framework. 4Q FY-08.**

Output Metric: Technical reports and papers, US patented algorithms, simulator demonstrations, and aircraft demonstrations.

Outcomes: (a) Valid algorithms for present transmission and engine monitoring applications, (b) Enabling technology available for commercial gear-drive engines, (b)

**L-IV Laboratory/Test Rig Research Infrastructure. (GRC continuing) 4Q FY-06.**

Output Metric: Conference or journal reports.

Outcome: Industry awareness of treatment variable effects on vibration patterns.

**L-V Obtain planetary data from undamaged components for healthy baseline. (Dempsey, GRC) 4Q04.**

Output Metric: Reference data.

Outcome: Ability to compare with planted faults.

**L-V Obtain data from damaged planetary components. (Dempsey, GRC) 4Q05.**

Output Metric: Technical report.

- Outcome: Initial validation of algorithms.
- L-V Seeded fault and accelerated fatigue tests. (Dempsey, GRC) 4Q05  
Output Metric: Test completion.  
Outcome: Evaluation of multivariate fault detection schemes on-line.
- L-IV **Flight Research Infrastructure** (ARC, ongoing). 4Q FY-06.  
Output Metric: Scientific data collected from OH-58C, UH-60L, and C-17 aircraft.  
Outcome: Ability to study vibration and oil debris signals in realistic operational environments.
- L-V Flight demonstration of VMEP/Healthwatch on Army/NASA UH-60L Black Hawk. (Huff, Mosher, Lee ARC) 4Q04  
Output Metric: Test completion. Published reports.  
Outcome: Availability of robust DSA method in flight for metric evaluation.
- L-V Installation of HW-3 on C-17. (Huff, Mosher, Lau) 4Q04  
Output Metric: Installation ready for flight.  
Outcome: Ability to sample and store high-speed engine data in flight.
- L-V Installation of HW-4 software upgrade. (Mosher, Lau) 4Q04  
Output Metric: Software installed and ready for flight.  
Outcome: Ability to evaluate engine health in flight using advanced data preparation and feature extraction methods.
- L-V C-17 Flight data analysis studies. (ARC/GRC/P&W ongoing) 4Q07  
Output Metric: Software installed and ready for flight.  
Outcome: Ability to evaluate engine health in flight using advanced data preparation, multivariate, and feature extraction methods.
- L-IV **Integrated Computational Diagnostics and Dynamics** (ARC/GRC, continuing). 4Q FY-07.  
Output Metric: Publications, conference presentations, patents.  
Outcome: Basic contributions to health monitoring knowledge base.
- L-V Statistical Modeling: Perform quantile analysis of power spectra in each PC axis of FY-03 OH-58C data. (Huff, Mosher, Barszcz) 3Q04.  
Output Metric: Publication of study.  
Outcome: Confirmation of state-space response surface analysis.
- L-V Multivariate Sensor Fusion: Develop diagnostic tool for combined gear/bearing vibration and oil debris analysis. (Dempsey, GRC) 4Q04.  
Output Metric: Diagnostic tool and research reports.  
Outcome: Conclusions about the potential for “fusion” of vibration and oil-debris information in real-time.
- L-V First Principles Modeling: Generate “normal” and damage signatures using finite-difference modeling. (Kaul) 2Q05.

		<u>Output Metric:</u> US patent for grid generation. Normal reference signatures. Selected damage signatures.
		<u>Outcome:</u> Ability to use reference signals for (a) flight data analysis and (b) a basis for synthesizing a hybrid fault database.
L-V		Hybrid Fault Database for Hit and False Alarm Determination. (Huff, Kaul, Mosher, Lee, tbd) 4Q05.
		<u>Output Metric:</u> Hybrid Fault Database with synthetic damage populated by Monte-Carlo techniques.
		<u>Outcome:</u> Ability to evaluate systematically “hits” and “false-alarms” of detectors and classifiers in the same framework.
L-V		Planetary Decomposition Algorithm. (Mosher) 3Q04.
		<u>Output Metric:</u> Publication.
		<u>Outcome:</u> US algorithm for use by rotorcraft industry in rotorcraft HUMS.
L-V		Planetary Decomposition Validation. (Mosher, Decker) 4Q05.
		<u>Output Metric:</u> Validation in test-rigs or flight.
		<u>Outcome:</u> Acceptance by rotorcraft industry.
L-V		Validate Multivariate Decision Fusion. (Dempsey, GRC) 4Q05.
		<u>Output Metric:</u> Conference or journal report.
		<u>Outcome:</u> Improved reliability of in-flight systems transmission or engine monitoring systems.
L-IV		Generalized Predictive Control. (Soloway, Kelkar)
L-V		Grant report 4Q FY-04 (see detail above)
		GIMO proposal 4Q FY-04 (based on NASA announcement)
L-IV		Research Database Development. (ARC Team, ongoing) 4Q06.
		<u>Output Metric:</u> Functional database available through internet.
		<u>Outcome:</u> Ability of US researchers and industry to access vibration database subject to export control regulations.
L-V		Incorporation of VMED database. (Lee, ARC) 4Q FY-04
		<u>Output Metric:</u> Comprehensive functional statement, documentation for Army/NASA.
		<u>Outcome:</u> Ability implement satisfactory system.
L-V		Database implementation (Lee, ARC). 3Q FY-04
		<u>Output Metric:</u> All current data included in database.
		<u>Outcome:</u> Ability to access data on demand.

## Resources / Budget

ARC

Labor:



6.65 FTE  
1.00 WYE

Procurement (excluding labor):

\$0.306M Procurement  
\$0.040M SERV-I

GRC

Labor:

1.50 FTE  
0.00 WYE

Procurement (excluding labor):

\$0.287M Procurement

## Management Approach

Deliverables (FY 2004):

- Research Technical Paper compliant with Ames Publication procedures (ARC 310 and ARC 1676), or equivalent procedural compliance for tasks located at NASA Glenn Research Center.
- Simulation / demonstration of technologies.
- Physical / experimental data acquisition and/or technology validation.

Environment / Equipment:

- All research will take place in the Neuroengineering Laboratory Rm. 281 / Bldg. 269, Flight simulation facilities (CVSRF in Bldg. 257 or the VMS in Bldg. 243), and Flight test assets (AFDD OH-58C and DFRC F-15 Tail No. 837).

Compliance with Standards and Codes:

- 53.ARC.0009.2.1 Publication of research
- 53.ARC.0009.2 Management and performance of research

Applicable Quality System Procedures and Work Instructions:

- 53.ARC.0004.1
- 53.ARC.004.2

## Process Monitoring Methods/Procedures:

- Performed to satisfy all Level I business requirements, described below:

Type	Frequency	Purpose	Reporting By	Content/Format	Comments
Technical Highlights	Weekly	Status updates and/or highlights	L4 Task Leads and Technical POCs	Informal text of monthly progress - indicate "None" for negative replies <i>e-mail text; web-site entry</i>	Unless significant progress is reported, can be brief
Quarterly	Quarterly	Program	L2 Managers	Text (and accompanying graphic, if	Progress towards all

Progress		Management Council (PMC)		any) of quarterly progress towards L1/L2 milestones <i>e-mail text; electronic copy of graphic; web site entry (under development)</i>	active L2/L3 milestones should be reported
Technical Highlights	Quarterly	Program advocacy and reviews	L2 Managers	One page text (Bullets: Objective, Background, Accomplishment, Future Plans) and one page graphic <i>e-mail text; electronic copy of graphic; web site entry (under development)</i>	Technical Highlights are used to promote the CICT Program and represent significant accomplishments
Milestone Summaries	Milestone due dates or completion	Program advocacy and reviews	L2 Managers	Detail description of milestone accomplishments relative to goals and success metrics. Background material including graphics, technical reports, publications, etc. <i>e-mail text, electronic copies of graphics, hardcopies of reports</i>	
Budget and Workforce Tracking	Monthly (5th working day of each month)	Status reports to ITSRO and CFO	Center POCs for resource management	Spreadsheets, graphs at the 5-digit level. Include variance explanation for +/- 10% variances <i>e-mail text; electronic copy of graphs; web site entry (under development)</i>	Planned vs. actual commitments obligations and accruals at 5-digit level. Planned vs. actual CS and SSC workforce.
ATAC Sub-committee Reviews	Annual	To review and provide advice on research efforts	L1, L2, and L3 Managers and Technical POCs	Program, project, and sub-project plan on-site review on status, approach, and technical accomplishments	
LCPMC	Annual	To review status, budget, and milestones	L1 and L2 Managers	Program and Project tracking of budget and milestones	

### Technical and Programmatic Risks

- Research in this program area is highly dependent upon the flow of reliable experimental data from both NASA aircraft and test rigs. Earlier studies have verified that recorded methods meet minimal reliability requirements.
- The installation and production of in-flight engine data is dependent upon good working relations with Dryden.

### Equipment and Suitable Work Environment

- The Code IC infrastructure of computers and software packages, e.g., MATLAB, LabView, and SPSS, is sufficiently well established to support the program.
- Adequate measuring equipment and computing hardware/software can be made available in the flight aircraft and test facilities.

## Compliance with Standards and Codes

n/a

## Process Monitoring Methods/Procedures

- Bi-weekly technical meetings are held in N-269 to coordinate several parallel efforts.
- Monthly status reports and telecoms are provided as required by Level 2 program office.
- Applicable Quality System procedures and work instructions are:
  1. ISO SLP 53.ARC.0009.2
  2. ISO SLP 53.ARC.0009.2.1
  3. ISO SLP 53.IC.0009-1

## ACQUISITION SUMMARY

*Provide summary information on procurement items, such as element (engineering design study, hardware development, mission and data operations support); type of procurement (competitive, AO for instruments; type of contract (cost-reimbursable, fixed-price); source (institutional, contractor, other Government organizations); procuring activity (NASA Center); and technical monitoring (NASA Center).*

With one exception, work in this program element will be done in-house by NASA civil service staff, or with support from Code IC support services contractor.

Grant: Prof. Atul Kelkar, Iowa State Univ., “...

## PROGRAM/PROJECT DEPENDENCIES

*Other NASA, U.S. agency, and international activities, studies, and agreements are summarized with emphasis on their effect on the program.*

- a. Related activities and studies, e.g., SOMO, Launch Services, crosscutting technology.*
- b. Related non-NASA activities and studies.*

Research activities are coordinated with US rotorcraft industry by interaction with NRTC and RITA. Coordination meetings with US Army and Navy, as well as DARPA, are arranged as needed.

## AGREEMENTS

*List all agreements necessary for project success and the projected dates of approval. This list shall include all agreements concluded with the authority of the project manager, and should reference agreements concluded with the authority of the Lead Center program manager and above.*

*a. NASA agreements, e.g., SOMO Service Level Agreements, Launch Services Agreements.*

*b. Non-NASA agreements.*

*(1) Domestic.*

*(2) International.*

No domestic or international agreements are necessary for the success of the research program.

## TECHNOLOGY ASSESSMENT

*Identify the NASA technology thrusts to be applied. Identify those technologies in the project that will mature during its life cycle.*

Health and Usage Monitoring Systems (HUMS).  
Real-Time Diagnostic and Prognostic Algorithms.  
Sensor Fusion (Multivariate).  
First Principles Finite Difference Modeling.  
Linear Predictive Control (LPC).  
Information Technology (IT).  
Artificial Neural Networks (ANN).

## COMMERCIALIZATION

*Identify near-term opportunities for commercialization. Describe the methods to be used to identify additional opportunities throughout the project's life cycle.*

1. Kaul
2. VMEP